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MEMORANDUM REPORT ARBRL-MR-02892

A FUEL FIRE MODEL FOR COMBAT VEHICLES

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January 1979

US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: MEMORANDUM REPORT ARBRL-MR-02892

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle): A FUEL FIRE MODEL FOR COMBAT VEHICLES

5. TYPE OF REPORT & PERIOD COVERED: Final

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s): James Dehn

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS:
U.S. Army Ballistic Research Laboratory
(ATTN: DRDAR-BLT)
Aberdeen Proving Ground, MD 21005

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: RDT&E 1L161102AH43

11. CONTROLLING OFFICE NAME AND ADDRESS:
USArmy Armament Research and Development Command
U.S. Army Ballistic Research Laboratory
(ATTN: DRDAR-BL)
Aberdeen Proving Ground, MD 21005

12. REPORT DATE: JANUARY 1979

13. NUMBER OF PAGES: 26

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)

15. SECURITY CLASS. (of this report): UNCLASSIFIED

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release, distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Fuel Fires
Combat Vehicles
Modeling

20. ABSTRACT (Continue on reverse side if necessary and identify by block number) (mba)

A descriptive model of an attack on the fuel cell of a diesel-powered ground combat vehicle is presented. The major factors which can contribute to a destructive, unchecked fire are examined and the probability of their occurrence is given a mathematical formulation. This model is also set in the general context of modeling.

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I. INTRODUCTION

In this report we will first put the proposed model in context by showing how it fits into the general subject of modeling. Then we will give a descriptive fuel fire model, followed by a mathematical formulation of this description. A later report will discuss methods of estimating the parameters and validating the results of the mathematical formulation.

The word model is used in many ways, sometimes as an ideal to be imitated or a pattern to be copied. We speak of a photographer's model and of clothing models (living or not). We build model airplanes and model Eiffel Towers. In science and technology we frequently perform small scale experiments to model the real world and invariably construct some sort of analytical model. In this report we are speaking of an analytical model which we will present in two forms, descriptive and mathematical. Before presenting the detailed model we will make a few remarks about modeling which bear repeating. It should only help to remind ourselves of well-known facts; for, to paraphrase Chesterton, the most important thing about a truism is that it is true.

1. A model should never be a substitute for experience. Even incomplete experience is more significant than an elaborate model if our goal is to deal with the real world. This experience could come from controlled experiments or it could come from systematic observation of uncontrolled events. A traditional example of the latter is the astronomer's observation of the sky. An example closer to home is combat data collection. No matter how incomplete it may be, it is still observational experience and any model we build should be guided by it and ultimately checked against it. Of course controlled experiments, especially those suggested by combat experience, can also help a great deal. More will be said about this in the discussion below.

The classic example of a model which lasted for centuries largely because of aesthetic bias was the geocentric model of the solar system. As experience gradually accumulated this model was repeatedly amended by adding one epicycle to another until the whole thing became rather intractable. This occurred in spite of simpler alternate models which were suggested. Eventually, a combination of experience and insight led to our present heliocentric model. Even this is not a complete description of the solar system, but it is good enough for many purposes.

To summarize, models with little if any observational validation are at best highly tentative and ought to be explicitly described as such. Values placed on models because of age or cost or complexity or aesthetics are no substitute for experience.

2. Making a mathematical model is not the only way to use our experience and it is not necessarily even the best way to use it. For

example, we could take combat data and use it to discover the weak points in our systems. In the process we would form some sort of descriptive analytical model although we might not write it down or even be fully conscious of doing so. Various remedies might then be suggested and we could use controlled experiments to test these remedies. Historically this procedure has been followed for Army helicopters and has proved to be very fruitful. No mathematical model is needed for this procedure. A great deal more of this could be done for Army ground vehicles than has been done. Unfortunately there is very little activity in this area.

If one has limited resources and is forced to choose, say between experimental vulnerability reduction and mathematical modeling, it would seem reasonable to choose experimental vulnerability reduction. To choose only mathematical modeling, especially modeling which is said to have little or no chance of validation except by methods involving prohibitive costs, is unprofitable. To choose only experimental vulnerability reduction however would not be unprofitable. With sufficient resources it would be desirable to do both. Of course the relative allocation of resources should be made in accordance with the ability of each method to attain the goal of improved fighting equipment. Similarly, experimental lethality might be better than modeling only, although a lack of knowledge about the targets could severely limit such activity. In such a case, modeling might be the only thing we can do, although the credence we place in our results will be severely limited by our inability to check them.

Eventually, we seek a mathematical formulation. To be useful, of course, this formulation should strike a balance between the amount of detail which is included and the need for simplicity as an aid to both understanding and use. The proper balance can only be reached by keeping in mind the purpose of making such a model, the improvement of fighting equipment. Ockham's razor is the proper tool for the job, namely, our model should be no more complicated than is necessary for the task at hand.

3. All mathematical simulations should include measures of accuracy and reliability and the precision which is used to express these measures should be appropriate. Unfortunately, there is no universal agreement on the use of these words, with statisticians meaning one thing and experimentalists meaning another in many cases. For clarity it will be necessary to say what we mean here in the case of analytical models.

Accuracy is a statement about the deviation which exists between our model and some chosen norm. It can be measured by combining various types of error into one resultant error. In the case of mathematical models the preferred norm is observational experience. Sometimes however one model is compared with another which has already been compared favorably with experience. This procedure is often followed in testing numerical schemes for solving complicated sets of equations. If closed form solutions are known which accurately describe simple cases then our numerical scheme should at least be able to reproduce the results of such solutions. If they can do this, then perhaps some temporary credence might be given to their solutions for more complicated cases to be later checked with experience.

Sometimes one mathematical model is compared with another which itself has not been validated by experience, but which is revered because of antiquity, complexity, cost or some other reason. The utility of this procedure is not evident, but at least it can yield some measure of accuracy. At least on one occasion there was a model maker who adopted this procedure and compared the results of a new model with an older, more complicated, equally unvalidated model. It was clearly stated that the older model was being taken as a norm and in most cases reasonable agreement was found between the old and the new. In one case, however, notable disagreement was found. Whereupon the model maker concluded that the older model (the norm) must be wrong. From one point of view we might be able to justify this abrupt change in gears, since the magnitude of the deviation is the same no matter which model we choose as norm. If we are not concerned with the real world, then the direction of the deviation does not matter. However, if our interest is in simulating the real world, then the direction of the deviation is primary and its magnitude is secondary, although very important. If we always choose experience as our norm then the direction of our model's error or deviation from the norm is established and we can proceed to determine its magnitude.

It is well-known that repeated experiments do not yield identical results. Indeed, one of the surest signs of "fudged" results is consistency beyond the capability of the equipment used. Fortunately this problem is usually encountered only in freshman laboratories. Mathematical simulations should also have their measure of reliability or repeatability if they are done correctly. The fact that they are carried out entirely inside the mind of the analyst or within the circuits of a digital computer does not exempt them from this requirement. Whether they are deterministic or stochastic is irrelevant.

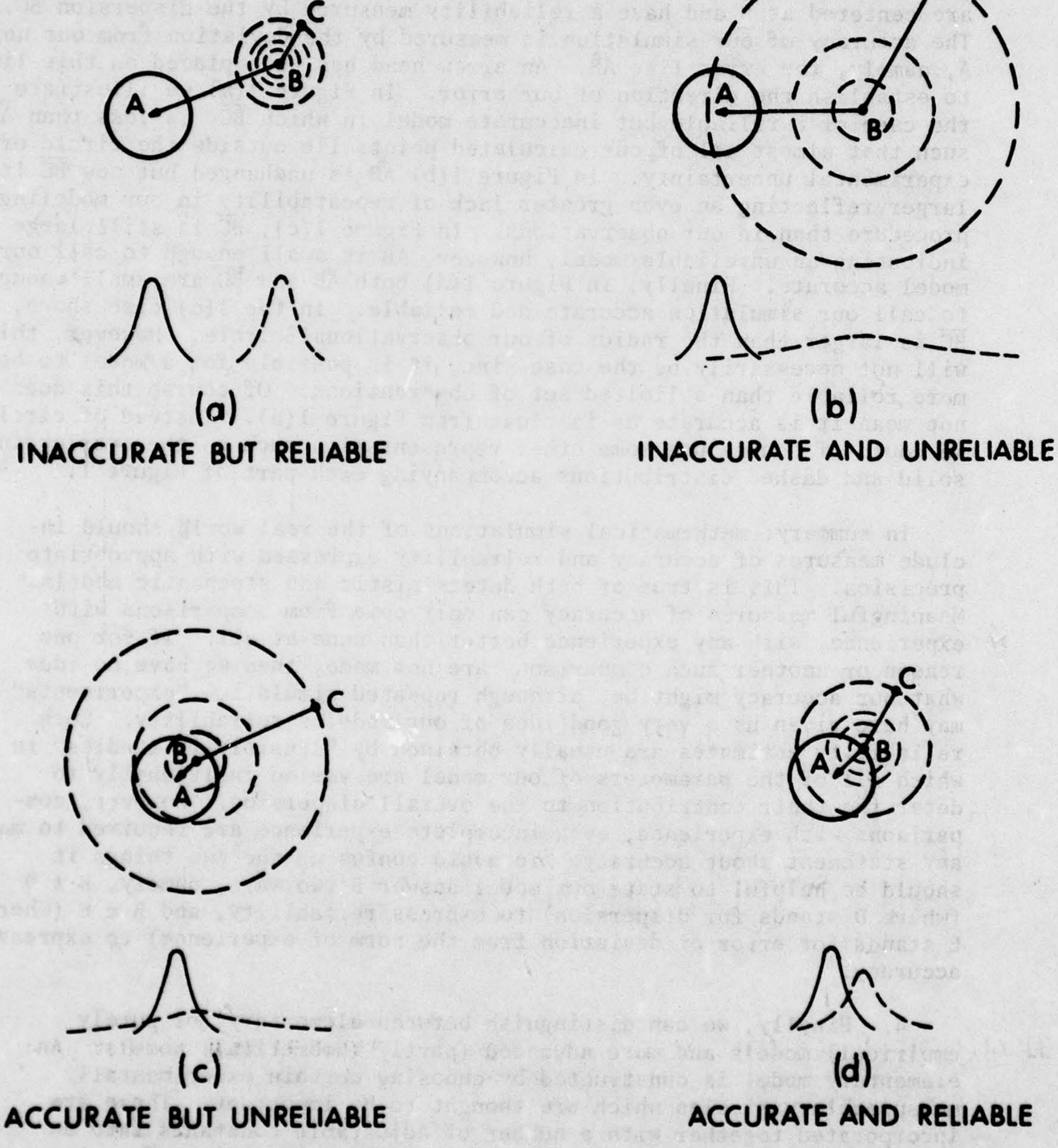
An example should help to clarify the above statements. Suppose we were to choose seven horizontal shot lines evenly spaced around a vehicle by 30° from 0° to 180° as representative of the infinite number of such lines which might be chosen. Moreover, all of these lines are at the same height above ground level, passing for example through the center of gravity of the vehicle. For each line we then calculate the probability of killing the vehicle according to some model prescription. Finally, we take some type of (generally weighted) average over the seven representative probabilities and call this the kill probability. If we repeat the same procedure a second time by resubmitting the same computer deck of course we get exactly the same answer to whatever precision we have set in our program. This is <u>not</u> what is meant by repeating a mathematical simulation "experiment". Suppose instead we chose a different number of lines the second time, spaced differently in an even or uneven but prescribed manner and not all passing through the center of gravity. Real warheads after all do not seek out the center of gravity, do not all enter at the same distance above the ground and do not all necessarily travel horizontally. Now our answer will be different even without changing our model prescription for each shot line or our averaging procedure. If we do a number of such "experiments", each perfectly deterministic, and even try different averaging procedures, we will begin to get a feel for the reliability or repeatability of our simulation technique. We can express the central tendency of our results by some measure such as a mean, a mode or a median and we can express the reliability of our results by some measure of dispersion like a variance or standard deviation. Of course it is also possible to use a stochastic method for choosing our shot lines in any given "experiment" if we let tables of random numbers guide our choices for the number, spacing and angularities of our lines. Again we will note central tendencies and dispersions for the ensemble of our results. However, if we always carry out only one "experiment", for example, seven horizontal lines evenly spaced and passing through the center of gravity, our results will reflect the bias of our single, arbitrary choice.

Compounding the uncertanties of our model will be the uncertainties of the experimental measurements which are used in most models. For example, if measured residual penetrator masses and speeds have uncertainties of ten or twenty percent, no amount of modeling can remove this uncertainty from the final result. Add to this the uncertainty introduced by the "propagation of errors" which is present in any even slightly elaborate calculation as well as the uncertainties which occur because of extrapolation beyond measured results. A very simple example of the "propagation of errors" is the calculation of a velocity from measured values of distance and time. An example of extrapolation is the "guesstimate" that an interior component such as a radio is equivalent in stopping power to x mm of steel, without actually measuring this stopping power. Complicated models are often filled with examples of such "guesstimates", a procedure fondly referred to as SWAG. It is especially difficult to estimate the contribution of this procedure to our overall error. The net result can be a rather uncertain final answer which is sorely in need of some kind of validation to check, for example, the difference between .3 ± .2 and .6 ± .2 at some confidence level which hopefully exceeds fifty percent. Assertions of greater accuracy than this are not demonstrations of accuracy. If indeed we are dealing with this level of uncertainty then second or third decimal place precision in the expression of our answer is inappropriate. Our computer may well be capable of twenty four place precision but we would hardly be tempted to retain such precision as significant.

A few illustrations should help to clarify the meaning of the terms accuracy and reliability as we are using them here. In each part of Figure 1 we have drawn a circle, the center of which represents the central tendency observed in our experience (obtained from controlled experiments and/or observations of uncontrolled events). The radius of this circle represents the reliability of our observations. Each part of this figure also contains a group of points with each point representing the outcome of an individual simulation "experiment". These points are centered at B and have a reliability measured by the dispersion $\overline{BC}$. The accuracy of our simulation is measured by the deviation from our norm, A, namely, the error line $\overrightarrow{AB}$. An arrow head has been placed on this line to establish the direction of our error. In Figure 1(a) we illustrate the case of a reliable but inaccurate model in which $\overline{BC}$ is less than $\overrightarrow{AB}$ such that almost all of our calculated points lie outside the circle of experimental uncertainty. In Figure 1(b) $\overrightarrow{AB}$ is unchanged but now $\overline{BC}$ is larger reflecting an even greater lack of repeatability in our modeling procedure than in our observations. In Figure 1(c), $\overline{BC}$ is still large indicating an unreliable model, however, $\overrightarrow{AB}$ is small enough to call our model accurate. Finally, in Figure 1(d) both $\overrightarrow{AB}$ and $\overline{BC}$ are small enough to call our simulation accurate and reliable. In the 1(d) case shown, $\overline{BC}$ is larger than the radius of our observational circle. However, this will not necessarily be the case since it is possible for a model to be more reliable than a limited set of observations. Of course this does not mean it is accurate as is clear from Figure 1(a). Instead of circles we could of course use some other representation such as the overlapping solid and dashed distributions accompanying each part of Figure 1.

In summary, mathematical simulations of the real world should include measures of accuracy and reliability expressed with appropriate precision. This is true of both deterministic and stochastic models. Meaningful measures of accuracy can only come from comparisons with experience, with any experience better than none at all. If for one reason or another such comparisons are not made, then we have no idea what our accuracy might be, although repeated simulation "experiments" may have given us a very good idea of our model's reliability. Such reliability estimates are usually obtained by "sensitivity studies" in which all of the parameters of our model are varied individually to determine their contribution to the overall dispersion. However, comparisons with experience, even incomplete experience, are required to make any statement about accuracy. To avoid confusing the two things it should be helpful to state our model answer B two ways, namely, B ± D (where D stands for dispersion) to express reliability, and B ± E (where E stands for error or deviation from the norm of experience) to express accuracy.

4. Finally, we can distinguish between elementary (or purely empirical) models and more advanced (partly theoretical) models. An elementary model is constructed by choosing certain experimentally measureable variables which are thought to be important. These are incorporated together with a number of adjustable constants into an arbitrary functional form which serves the *ad hoc* purpose of at least qualitatively representing the correct behavior of the variables. The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(d)
ACCURATE AND RELIABLE

Figure 1

constants are then adjusted to give a reasonable or even "best" fit to the data which is available over certain ranges of the variables. The final result is an interpolation formula which is useful at least within these measured ranges. Since extrapolation is not within the capability of such a model because it is not based on physical laws, it should at least be simple enough to serve as an aid to understanding or mentally organizing the data and preferably also be simple enough to facilitate calculations. More advanced models also select variables and usually include adjustable parameters, but the mathematical forms into which they are cast are based on physical laws. Because of this they can be used with some confidence for extrapolation, depending on how well the model represents the data which was used to determine the adjustable parameters and on the extent of the agreement between model predictions and other data which was not used in this way.

In this report we will present an elementary or purely empirical model of fuel fires. This choice is made partly because of the extreme complexity which would result if a more fundamental approach based on physical and chemical laws were used. In addition, if any use is to be made of such a model either for understanding or computing it should be simple. We will look upon the occurrence of a destructive diesel fuel fire in a vehicle which has just been attacked as a series of chance events which take place in the fairly short time between the moment when a penetrator defeats a fuel cell and the time when a destructive, unextinguished fire is established.

II. A DESCRIPTIVE FUEL FIRE MODEL

The following simplified description might serve our purpose.

Let us consider a single shot line through the diesel fuel in one cell of an operating vehicle (Tank, Carrier or Infantry Fighting Vehicle). At this point we will not specify anything more about the location or angularity of this shot line. The armor which has just been pierced is typically steel or a pyrophoric material, aluminum. A cloud of debris from the armor peppers the rear wall of the fuel cell and some particles pierce it. However, only those particles which have upward trajectories have much chance of exiting the fuel and possibly igniting the fuel-air mixture in the ullage space above the fuel. With diesel fuel this mixture will normally not be flammable although the splashing created by the particles just mentioned or by the motion of the vehicle can possibly make a flammable mixture in the ullage. Burning aluminum particles perhaps torn from the fuel cell itself would have more chance of igniting the ullage mixture than steel particles. It is also possible for the ullage to contain a flammable mixture before an attack because of operational heating of the fuel. The main penetrator (which might be typically a steel, tungsten or uranium alloy projectile or a copper shaped charge jet) opens holes on both the entrance and exit sides of the fuel cell which are much larger than the projectile diameter. In the case of the thin-walled aluminum fuel cells which are used in current US combat vehicles, the petaling mode of failure is greatly enhanced by hydrodynamic ram effects which themselves can be increased by projectile tumbling or breakup. These effects also lead to seam splitting, especially in the bottom half of the fuel cell. The net result is the simultaneous emission of clouds of fuel spray from the entrance and exit holes and a pouring of liquid fuel onto the vehicle floor from the split seams and from the entrance and exit holes.

Part of the fuel spray from the entrance hole may exit the vehicle especially if this hole is close to the armor hole, but part of it will spread and mix with air and ignition sources in the space between the armor and the fuel cell. Integral fuel cells which use the armor as one wall of the fuel cell do not seem to be in current use. In some cases the fuel cell may be near the center of the vehicle compartment. The fuel spray from the exit hole will also spread and mix with air and ignition sources which may have been present before the attack or perhaps are generated by the attack. For example, hot surfaces such as engine exhaust manifolds might already be present while short circuited electrical wiring, sparks or burning pyrophoric particles might result from the attack. Tungsten or steel for example will spark briefly while burning uranium particles will ricochet about much longer. Steel armor will spark but finely divided debris from both interior walls of aluminum armor can burn in white hot clouds. If the fuel sprays meet such ignition sources they will burn in fire balls on each side of the perforated fuel cell. As is well known, the ignition of diesel spray does not depend on fuel or ambient temperatures but only on spray mixing with air and ignition sources. This is the reason home oil burners are so reliable. The ignition of thin films of fuel on hot metal surfaces is a function of fuel composition and surface temperature. Ignition of a pool of spilled fuel is however somewhat temperature dependent. When the burning spray migrates under the action of gravity to the surface of the spilled fuel, the flame temperature of the fireball is sufficient to start the vaporization-burning-heat feedback cycle which is required for a pool fire to be self sustaining. When the original spray fireballs have been consumed the pool fire is on its own to grow and spread or die.

Another event can occur to assist a developing pool fire. If the ullage space inside the fuel cell has ignited it can build up interior pressures which can erupt as two jets of fire from the entrance and exit holes as soon as the liquid level in the cell has dropped to that of the holes. These jets can spread and fill the interior of the vehicle with flame, giving renewed impetus to a pool fire. Such jets usually occur a few seconds after impact and last for several more seconds.

It is possible for a stream of cold liquid diesel fuel to quench a struggling pool fire which is limited to the area hit by the liquid stream, but this is not likely to happen in an operating vehicle, especially one which has an engine that uses the majority of the fuel pumped to the combustion chambers for cooling the injectors and then dumps it back into the fuel storage cell. This is true of all fielded US engines. Because of the heat which is carried back to the fuel cell, the bulk of the stored fuel gradually heats up. As time passes in a mission and the fuel level drops, there is less fuel to act as a heat sink. Some heat is lost through the walls of the fuel cell to the surrounding air, but this effect is reduced if the temperature of the compartment air is above the ambient temperature as it is especially in an engine compartment. Heat losses might be expected to be greater in a crew or passenger compartment. However, these losses will be reduced by insulating material deliberately placed on fuel cell walls to prevent burns or discomfort to personnel leaning against the fuel cells. In the M113-A1 carrier for example, temperatures more than 50°F above the ambient have been found after a few hours into a mission. If the ambient temperature is 80°F or higher, the stored fuel will be above the minimum flash point required in the purchase specification, namely, 122°F. In other words under such conditions diesel fuel can be as flammable as gasoline.

The ambient temperature can possibly influence events in another way. If the metal floor onto which the fuel spills is cold, even hot diesel fuel can be cooled back down below its flash point. The depth of the liquid pool which is being formed at any point will also be a factor since the deeper the pool the less the floor temperature will affect the temperature of the pool surface and the more important will be the effects of the compartment air temperature and the fireball or jet which impinges on the pool surface. In engine compartments the floor and air temperatures will be considerably above the ambient temperature because of heat generated by the engine and not completely removed by cooling systems. In crew or passenger compartments personnel heaters are often used on cold days to warm the interior. All of this presents a complicated time- and space-dependent picture of temperature variations which we will try to represent in a simple "effective" manner.

Another factor required for pool fire growth to levels destructive of materiel is an adequate air supply. This is usually not a problem in operating vehicles as opposed to certain static simulations. In crew or passenger compartments provision must be made for ventilation. This ventilation can be increased if the attack itself pops open hatches which were initially closed or prompts occupants to open them, providing additional air intakes and combustion product vents. Air-breathing engines are located in compartments which have grilles on both the top and the rear in the case of Tanks. For example, the 1790 Tank engine uses two large fans to draw cooling air through the top grille, circulate it around the engine and fuel cells and then force it out the rear grille. Such forced convection in addition to natural convection will fan a fuel fire and assist its growth and spread. When a fire in a Tank engine compartment is discovered by the crew (by visual observation in present vehicles) they may take actions to extinguish it. They may also abandon the vehicle. If they stay and fight the fire they may first try to do so by manually releasing a bottle of extinguishing agent. Even if the extinguishant system is in proper working order, this procedure is usually not successful since the agent is swept out of the compartment by the cooling air flow before it has a chance to work. The next step is to shut down the engine, wait until the engine driven fans have stopped, then manually release the last shot of extinguishant. If the fire has not grown beyond control by this time, it may be extinguished. If it is not extinguished the lack of forced air convection by the cooling fans will not leave the fire oxygen-starved. If the fire is well enough established that it survives the second shot of extinguishant it can readily reverse the previous air flow pattern, sucking fresh air through the rear grille and pushing combustion products out the top grille. Previous attempts to experimentally simulate fuel fires in Tank engine compartments failed to include a second grille on the rear or side of the simulator box and only had a grille on top. This resulted in a predictable prevention of fresh air intake through the same top grille which served as a vent for hot, rising combustion products. An interesting possibility for extinguishing a fire is a method in which flaps are used to close all grilles or other vents. This would be effective but is certainly not desirable in crew or passenger compartments. Other procedures are also more desirable for engine compartments. For example, prompt automatic detection and extinguishant release without engine shut down but with cooling fan clutching and braking is a possibility.

If a fuel fire does resist attempts at extinguishment then it will spread from one compartment to another. For example, a Tank engine compartment fire will migrate via the bilge into the crew compartment, spreading along paths followed by the spilled fuel or provided by bilge grease and grime. The wicking effect of such material can also aid fire survival of extinguishment attempts. Once fuel fires have access to stored ammunition the time to irreparable damage is considerably shortened. Continuous bilge paths are maintained to meet drainage requirements after fording.

III. A MATHEMATICAL FORMULATION OF THE MODEL

Let us view the attack described in the previous section as a compound chance event. If P(S) is the probability that an ignitable spray is formed and P(SI/S) is the probability that it is ignited once it is formed, while P(P/S, SI) is the probability of a sustained pool fire, given spray formation and ignition, and P(EF/S, SI, P) is the probability of extinguishment failure, given the previous three events, then we can formally write the probability that all four events, S, SI, P and EF, will occur in that order as

$$P_4 = P(S)P(SI/S)P(P/S,SI)P(EF/S,SI,P) \qquad (1)$$

$$= P_3\, P(EF/S,SI,P). \qquad (1a)$$

All four events must occur before a destructive fuel fire will result in an operating vehicle and we label this compound event probability P_4. The definition of P_3 is obvious from Equation (1a). It is separately defined for convenience, partly because it is usually the only probability which is addressed in most fuel fire experimentation and partly because of the greater uncertainty of P(EF/S,SI,P).

If we had a great deal of data we could proceed to construct or choose probability functions which represented the data over the observed ranges fairly well. Still, the only reason for choosing one function rather than another would be a compromise between its ability to represent the data and any requirements we might set for simplicity. Such a model is purely empirical since no physical laws are used in selecting functional forms. Since the data we have is limited, it could be argued that we should wait until more data is available before choosing specific functions. On the other hand, the construction of a cart can sometimes generate the need for a horse. In other words, a suggestive model can sometimes stimulate further experimentation which could eventually lead to its usefulness. With this in mind we will attempt to choose functions which contain enough detail to suggest further work, yet not so much that they will impede understanding or discourage calculation.

After the armor has been perforated, the residual penetrating power of the projectile or jet can be expressed for example in terms of the number of centimeters of steel needed to stop it completely. We will call this residual S_{st}. Next, the projectile or jet perforates the fuel cell and part of the residual S_{st} is used in perforating the cell and creating a fuel spray. We will use the symbol R to represent the ability of the residual penetrator to create a fuel spray and our calculation will begin by assuming that R is known. At the present time the relation between R and S_{st} is not generally known and must be determined experimentally. This should not be hard to do. It is probably wrong to equate R and S_{st} since spray producing ability is more closely connected with the ability of the penetrator to transfer its energy to the fuel than with its ability to pass through the fuel. For example, a tumbling projectile might have a lower S_{st} than one which is flying end on, but its R could well be greater. Above a certain maximum R_M additional spray does not seem to further increase the likelihood of ignition (as determined by observations already made). To approximate this behavior, let us consider the following probability density function where C and R_M are real, positive numbers as will be all the variables and parameters chosen below.

$$f(r) = \frac{CR_M}{r^2(R_M/r - 1)^2} \exp\left[-C/(R_M/r - 1)\right] \qquad (2)$$

which is defined and positive for $0 < r < R_M$ and vanishes for values of r outside this range. Its cumulative value over the entire range is unity, so it is a probability distribution. This may be demonstrated by changing to the variable $x = 1/(R_M/r - 1)$ so that

$$\int_0^{R_M} f(r)\,dr = C\int_0^{\infty} e^{-Cx}\,dx = 1. \tag{3}$$

For a residual such that $0 < R < R_M$ we have

$$P(S) = \int_0^{R} f(r)\,dr = 1 - \exp\left[-C/(R_M/R - 1)\right]. \tag{4}$$

Now $P(S) = 0$ for $R \leq 0$ and $P(S) = 1$ for $R \geq R_M$ with the parameters C and R_M determining how rapidly P(S) approaches unity as the variable R increases over the defined range. These parameter values and the value of R will be related to fuel cell and compartment configuration, fuel viscosity and hydrodynamic ram effects as well as munition type, size and striking characteristics.

Next let us consider the likelihood of spray ignition once it has been formed. This depends on the existence or generation of ignition sources. Often ignition sources generated by the attack dominate the scene. They are not present initially but they rapidly grow in number until they reach a peak value mixed more or less widely with spray and eventually disappear. The greater the mixing of ignition sources and spray the more likely is ignition. This type of behavior might be approximated by a gamma distribution

$$f(t) = \frac{1}{\alpha!}\,\beta^{\alpha+1}\,t^{\alpha}\,e^{-\beta t} \tag{5}$$

accumulated over the time τ during which the spray and ignition sources form, mix and settle to the floor. If α is zero or integer the integration is simple, otherwise tables or numerical methods must be used. However, if $\alpha = 0$, the gamma distribution reduces to the exponential distribution which has its largest value at $t = 0$, which is not appropriate for this event. If $\alpha = 1$ we have

$$P(SI/S) = \int_0^{\tau} \beta^2\,t\,e^{-\beta t}\,dt = 1 - (1 + \beta\tau)\exp(-\beta\tau) \tag{6}$$

which of course is unity if $\tau = \infty$. For given τ (say 3 sec) the value of P(SI/S) increases as β increases. As the mixing frequency β becomes very large for any finite τ, P(SI/S) $\rightarrow$ 1. This is what happens in the case of aluminum armor perforated by a shaped charge jet when fine spall and ejecta particles burn in white hot clouds. It also can happen in the case of a properly designed uranium penetrator which breaks up into small burning chunks which further subdivide as they burn and ricochet about.

In some cases ignition sources may be present before the attack. We might approximate the combination of pre-existing and generated ignition sources by the following density function

$$f(t) = e^{-\gamma t} \left[\beta^2 t e^{-\beta t} + \gamma(1 + \beta t) e^{-\beta t}\right] \tag{7}$$

which reduces to Equation (5) with $\alpha = 1$ when $\gamma = 0$. In contrast to Equation (5) which is zero for $t = 0$, Equation (7) is equal to γ when $t = 0$. Here γ is a fractional number which represents the contribution of ignition sources which are present throughout the attack. Now we have

$$P(SI/S) = \int_0^\tau f(t)dt = 1 - (1 + \beta\tau) \exp\left[-(\beta + \gamma)\tau\right] \tag{8}$$

which reduces to Equation (6) when $\gamma = 0$ and is unity for $\tau = \infty$.

When a burning spray touches the surface of the spilled fuel, the flame readily initiates the evaporation-burning-heat feedback cycle which is characteristic of a pool fire. However, when the spray fire dies out this cycle must be self-sustaining for a pool fire to remain and grow. Wicks in the form of floor dirt will aid this process. Now a continued supply of fresh air as well as a vent for combustion products are required and are always available in real, operating vehicles. Forced convection in addition to natural convection will further assist fire spread over the pool up to some maximum value beyond which a law of diminishing returns sets in and a maximum rate of fire spread is achieved. Another factor influencing fuel fire growth will be the temperature of the spilled fuel. As described above this will be a complicated function of space and time which might be represented by an effective pool surface temperature intermediate between the higher temperature T_1, to which it had been heated in the fuel cell and the lower temperature T_2 of the floor. A higher spilled fuel temperature will favor pool fire spread up to some maximum value approaching the flash point of the fuel. Above this critical temperature T_c the mechanism of fire spread abruptly changes. Below this temperature diesel fire spread is controlled largely by liquid circulation phenomena.

Above this temperature the mechanism is the same as fire spread over spilled gasoline, namely, fire flash through the flammable vapor mixture above the pool.

Let us select air flow A and pool surface temperature T as two important variables to be incorporated into a bivariate distribution function which exhibits saturation behavior at A_c and T_c and has minimum values A_o and T_o. Consider the density function with parameter ε $(0 < \varepsilon < 1)$

$$f(x,y) = \frac{(1-\varepsilon)}{(T_c-T_o)} \frac{K_1(A_c-A_o)}{(x-A_o)^2\left(\frac{A_c-A_o}{x-A_o}-1\right)^2} \exp\left[-K_1/\left(\frac{A_c-A_o}{x-A_o}-1\right)\right]$$

$$+ \frac{\varepsilon}{(A_c-A_o)} \frac{K_2(T_c-T_o)}{(y-T_o)^2\left(\frac{T_c-T_o}{y-T_o}-1\right)^2} \exp\left[-K_2/\left(\frac{T_c-T_o}{y-T_o}-1\right)\right] \tag{9}$$

for $A_o < x < A_c$ and $T_o < y < T_c$ and $f(x,y) = 0$ for other values of x and y. Now the probability of a pool fire becomes

$$P(P/S,SI) = \int_{A_o}^{A} dx \int_{T_o}^{T} dy\, f(x,y)$$

$$= (1-\varepsilon)\left(\frac{T-T_o}{T_c-T_o}\right)\left\{1 - \exp\left[-K_1\left(\frac{A-A_o}{A_c-A}\right)\right]\right\} \tag{10}$$

$$+ \varepsilon\left(\frac{A-A_o}{A_c-A_o}\right)\left\{1 - \exp\left[-K_2\left(\frac{T-T_o}{T_c-T}\right)\right]\right\}$$

this can be shown by using the transformations

$$u = 1/\left(\frac{A_c - A_o}{x - A_o} - 1\right) = \left(\frac{x - A_o}{A_c - x}\right) \text{ and } w = 1/\left(\frac{T_c - T_o}{y - T_o} - 1\right) = \left(\frac{y - T_o}{T_c - y}\right).$$

When $A = A_c$ and $T = T_c$, then $P(P/S,SI) = 1$, while for $A = A_o$ and $T = T_o$, $P(P/S,SI) = 0$. The parameter ε serves to weight the relative effects of A and T to some extent while K_1 and K_2 help to control the rate at which these effects reach their maximum.

Finally, let us consider the extinguishment system which currently consists of two main components, the crew (CR) which must detect the fire and activate the extinguishing equipment (EQ). We will look upon these components as two independent links in a very short chain. In a vehicle where the fuel cell is located in an occupied compartment detection will be very prompt. Activating the equipment however may be another matter. Collecting one's wits takes various amounts of time for different people. The desire to escape a large spray fire and growing pool fire can be very strong, especially if it is thought that the available extinguishers are inadequate for the task. Small hand-held extinguishers such as are currently fielded in some vehicles are no match for large fires. Moreover, even such simple equipment may not always be in working order. The frosting effect of CO_2 extinguishers for example has been found useful for cooling a cola when the nearest refrigerator is miles away, so empty extinguisher bottles not necessarily caused by leakage may occur. Fire inspectors have also found such things as hardened wads of gum jamming manual release pins, making prompt activation almost impossible. Even automated equipment can have its troubles and there is truth to the notion that the more complicated a piece of equipment the more things there are which can go wrong. In Vietnam for example a number of automated bottles were installed in personnel carriers. After a time an inspection revealed such things as broken electrical wires, stuck valves, and nozzles blocked with clothing or other equipment. Complaints about the space taken up by large extinquisher bottles might eventually have led to cases of bottle removal to make way for more important cargo. In a vehicle such as a Tank where the fuel may be in an unoccupied engine compartment, visual detection of a fire may take sometime. Since hostile action is taking place the crew is occupied with fighting and will be reluctant to shut down the engine even if a little smoke is seen. By the time visible flames are observed the first extinguishant shot in an air-cooled engine compartment will almost certainly fail. Engine shutdown then takes additional time. By this time the crew may have decided to leave their stationary vehicle and perhaps use the extinguishant release lever on the exterior of the vehicle. Again the question of equipment maintenance and reliability arises, even assuming an adequate design of the equipment for the purpose of extinguishing large fires.

To represent this situation consider the probability of failure of a two-link chain, namely,

$$P(EF/S,SI,P) = 1 - [1 - P(CRF)]\,[1 - P(EQF)] \qquad (11)$$

where the probability P(CRF) that the crew will fail might be approximated by a cumulative exponential distribution

$$P(CRF) = 1 - \exp\,(-\,\lambda_1\tau_1) \qquad (12)$$

with λ_1 representing a failure rate and τ_1 representing a total delay time. If the crew does not activate the equipment for one reason or another, τ_1 is effectively infinite and P(CRF) = 1, breaking the chain and making Equation (11) unity also. In an automated detection and discharge system P(CRF) = 0. Similarly the probability of equipment failure might be approximated by

$$P(EQF) = 1 - \exp\,(-\,\lambda_2\tau_2) \qquad (13)$$

where λ_2 is an equipment failure rate and τ_2 is the time since the equipment was last successfully tested with perhaps an age factor included.

If we put Equations (4), (8), (10), (11), (12) and (13) in Equation (1) we obtain

$$P_4 = [1 - \exp\{-\,C/(R_M/R - 1)\}]\,[1 - (1 + \beta\tau)\exp\{-\,(\beta + \gamma)\tau\}]$$

$$\times\left[(1-\varepsilon)\left(\frac{T-T_o}{T_c-T_o}\right)\left\{1 - \exp\left[-\,K_1\left(\frac{A-A_o}{A_c-A}\right)\right]\right\}\right.$$

$$\left.+\,\varepsilon\left(\frac{A-A_o}{A_c-A_o}\right)\left\{1 - \exp\left[-\,K_2\left(\frac{T-T_o}{T_c-T}\right)\right]\right\}\right] \qquad (14)$$

$$\times\,[1 - \exp\{-\,\lambda_1\tau_1 - \lambda_2\tau_2\}]$$

which contains six variables and twelve adjustable parameters.

Our choice of functions is based on their ability to represent at least qualitatively the observations which have already been made. As these observations are refined other more suitable functions may be substituted.

IV. DISCUSSION

In this report we first set the stage for a fuel fire model by showing how it fits into the general subject of analytical modeling. Then we presented a descriptive fuel fire model followed by a mathematical formulation (accompanied by further descriptive details). The final formula, Equation (14), could be criticized from at least two points of view. A case could be made that it is too simple to represent adequately such a complicated phenomenon. Other variables should be included instead of ignored while certain factors should be made explicit instead of being lumped together in single parameters. Another case could be made that this formula is too complicated to be useful either by itself or as a submodel in an overall vehicle model which is already too complicated. The resolution of these and other points of view remains to be seen and is one reason for terminating the report at this point. If agreement can be reached on what is a useful compromise between complexity and simplicity and which mathematical forms might be more useful, then the work can resume. Obviously some observations have already been made, otherwise this model could not have been constructed. However, more observations should be made to put meat on the bare bones presented here. Then, as indicated in the introduction, the model should be exercised in a variety of simulation "experiments" and the factors influencing its reliability should be determined. Finally, its predictions should be compared with experience, preferably combat data, in order to establish its accuracy.

It has been objected that combat data cannot be used to check such models since the cases are too few and the reporting too inconsistent or unreliable. What we need are hundreds of controlled experiments which regretably are too costly to perform. Consequently, we must rely on the opinion of the analyst that his model is both reliable and accurate.

If this objection is correct, then it is not worthwhile to spend any resources on such modeling. Even if such models were shown to be reliable, they cannot reasonably be used for practical vulnerability or lethality requirements if they are not also shown to be accurate. They may very consistently give the wrong answer.

The objection also fails to distinguish between different sets of combat data. Some sets may be limited to hole-counting of biased samples by non-eyewitnesses. But other sets contain detailed descriptions of individual cases by both eyewitnesses and trained observers who made every effort to obtain representative samples. In some cases we even have complete populations.

In addition the objection fails to recognize the uncertainties which should be attached to the model answers themselves, some of which have been mentioned in the introduction. Should the reliability of these answers be expressed to third or even second decimal place precision? Probably not. The burden of proof is on the analyst to show the extent to which even his first decimal place is reliable. No amount of assertion can substitute for demonstration. If only one set of shot lines is used in one simulation "experiment" then our model answer is very unreliable. To achieve a 95% confidence level that our answer is B ± .1 where 0 < B < 1 we would need a hundred simulation "experiments" in the absence of prior knowledge of the answer. For B ± .01 we would need ten thousand "experiments".

What can be achieved with a limited number of observed cases as found in combat data? Again, if we insist on a 95% confidence level that our observational answer be A ± .1, we need a hundred cases. However, for an 80% confidence level that our answer be A ± .2 we only need ten cases, a number which is often found in combat data sets. By insisting on an unrealistic and unnecessary goal, the objection raised above refuses to consider the preferred way by which our model accuracy should be checked. The outlook is not necessarily as bleak as this objection suggests. We should check our accuracy wherever and to whatever extent we can, since some light is better than total darkness. By knowing the reliability of the combat data answer A we will also have a better idea of how much reliability is needed for our model answer B. In terms of Figure 1, once we know the radius of the circle with center A, we can better decide on a value for $\overline{BC}$ and the number of simulation "experiments" which are required. Having done all this we can estimate our accuracy $\overrightarrow{AB}$.

Fortunately, descriptive models can be useful without any mathematical formulation at all and even if they are never verbalized explicitly. For example, something like the descriptive fuel fire model given above has already been used at least implicitly by various people in the field of vulnerability reduction. Some of their efforts have now been gathered into an Army program called FISCOV for Fire Survivability of Combat Vehicles. Anti-misting agents have been added to diesel fuel to prevent or reduce spray formation. Spall suppressant materials such as foam or Kevlar have been suggested to reduce the number of ignition sources generated by an attack. Thin auxiliary cells filled with water or liquid halon have been tested to prevent spray ignition and reduce fuel spillage from hydrodynamic ram effects. Halon and water additives to diesel fuel have been used to prevent pool fires or cause them to be self-extinguishing. Automatic fire detection and extinguishant discharge systems have been designed for the XM1 Tank and retrofits are planned for older vehicles. In some cases plastic fuel cells are being used instead of aluminum while in other cases fuel cells are to be placed external to the vehicle. This list could be made longer but should be enough to illustrate the point. A great deal can be done with purely descriptive models. Much more remains to be done in other areas which are largely untouched.

Giving descriptive models a mathematical form is not too difficult. But determining suitable parameter values, exercising these models to determine their reliability, and comparing their results with observational experience in order to determine their accuracy so that we can reasonably use them for practical vulnerability/lethality predictions requires a great deal of effort. Perhaps it will be worth the effort, perhaps not. This remains to be demonstrated.

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